Intrinsic Channel Properties, Scattering Mechanisms, Quantum Transport Properties in Transition Metal Dichalcogenides

by

Kraig Andrews

DISSERTATION

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Approved by:

Advisor

This is a dedication.

“The fact that we live at the bottom of a deep gravity well, on the surface of a gas covered planet going around a nuclear fireball 90 million miles away and think this to be normal is obviously some indication of how skewed our perspective tends to be.”

— Douglas Adams, The Salmon of Doubt: Hitchhiking the Galaxy One Last Time

ABSTRACT

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Major: Physics

Degree: Doctor of Philosophy

Abstract here

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Acknowledgements here

Table of Contents

List of Figures

List of Tables

List of Symbols

Symbol	Description	Unit
$\mathbf{A}$	vector potential	$\mathrm{V\,s\,m^{-1}}$
A	area	$\mathrm{cm^2}$
$A^\star$	Richardson's constant	$\mathrm{A\,s^{-1}\,K^2}$
B	magnetic field	T
C	capacitance	F
E	electric field	$\mathrm{V\,m^{-1}}$
E	energy	eV (J)
E_F	Fermi energy	eV
E_g	bandgap energy	eV
$\hat{\mathbf{H}}$	Hamiltonian	eV (joule)
I	current	A
I_ds	drain current	A
L	length	µm
L	channel length	µm
m	mass	kg
$m^\star$	effective mass	kg
n	carrier density	$\mathrm{cm^{-2}}$
n	charge carrier density	$\mathrm{C\,cm^{-2}}$
$\hat{\mathbf{p}}$	momentum operator	$\mathrm{kg\,m\,s^{-1}}$
R	resistance	$\mathrm{k\Omega\,\mu m}$ (Ω)
R_c	contact resistance	$\mathrm{k\Omega\,\mu m}$
R_H	Hall coefficient	$\mathrm{m^3\,C^{-1}}$
$\hat{\mathbf{s}}$	spin operator	$\hbar$ (J s)

T	temperature	K
V	voltage	V
V_{bg}	backgate voltage	V
V_{ds}	drain voltage	V
V_{H}	Hall voltage	V
w	channel width	µm
μ	mobility	$\mathrm{cm^2\,V^{-1}\,s^{-1}}$
μ_{B}	magnetic moment	$\mathrm{eV\,T^{-1}}$
μ_e	electron mobility	$\mathrm{cm^2\,V^{-1}\,s^{-1}}$
μ_{FE}	field-effect mobility	$\mathrm{cm^2\,V^{-1}\,s^{-1}}$
μ_{H}	Hall mobility	$\mathrm{cm^2\,V^{-1}\,s^{-1}}$
μ_p	hole mobility	$\mathrm{cm^2\,V^{-1}\,s^{-1}}$
ρ	resistivity	$\Omega\,\mathrm{cm}$
ρ_{xx}	longitudinal resistivity	Ω
ρ_{xy}	transverse resistivity	Ω
σ	conductivity	µS
σ_{xx}	longitudinal conductivity	µS
σ_{xy}	transverse conductivity	µS
τ	scattering time	s
τ_{q}	quantum scattering time	s
Φ_{B}	barrier height	eV
$\Phi_{\mathrm{B}n}$	electron barrier height	eV
$\Phi_{\mathrm{B}p}$	hole barrier height	eV
Φ_M	metal work function	eV
Φ_S	semiconductor work function	eV
χ	electron affinity	eV
χ_S	semiconductor electron affinity	eV
ω_c	cyclotron frequency	Hz

List of Physical Constants

Symbol	Quantity	Value
μ_B	Bohr magneton	$9.274\,009 \times 10^{-24}\,\mathrm{J\,T^{-1}}$
		$5.788\,381 \times 10^{-5}\,\mathrm{eV\,T^{-1}}$
		$e\hbar/2m_e$ (atomic units)
k_B	Boltzmann's constant	$1.380\,66 \times 10^{-23}\,\mathrm{J\,K^{-1}}$
ϵ_0	Dielectric constant	$8.854\,18 \times 10^{-12}\,\mathrm{A^2\,s^4\,kg^{-1}\,m^{-3}}$
		$8.617\,34 \times 10^{-5}\,\mathrm{eV\,K^{-1}}$
e	Elementary charge	$1.602\,18 \times 10^{-19}\,\mathrm{C}$
m_e	Electron mass	$9.109\,383 \times 10^{-31}\,\mathrm{kg}$
eV	Electron volt	$1.602\,18 \times 10^{-19}\,\mathrm{J}$
c	Speed of light	$2.997\,92 \times 10^{8}\,\mathrm{m\,s^{-1}}$
h	Planck's constant	$6.626\,07 \times 10^{-34}\,\mathrm{J\,s}$
μ_0	Permeability in vacuum	$1.256\,63 \times 10^{-6}\,\mathrm{m\,kg\,s^{-2}\,A^{-2}}$
		$4\pi \times 10^{-7}\,\mathrm{m\,kg\,s^{-2}A^{-2}}$
$\hbar$	Reduced Planck's constant	$1.054\,57 \times 10^{-34}\,\mathrm{J\,s}$ $(h/2\pi)$
$k_\mathrm{B}T$	Thermal energy	$0.025\,86\,\mathrm{eV}$ $(T = 27^\circ\mathrm{C})$
		$0.025\,26\,\mathrm{eV}$ $(T = 20^\circ\mathrm{C})$
$R_{\mathrm{K}-90}$	von Klitzing constant	$25\,812.807\,455\,55\,\Omega$

Source: CODATA Recommened Values of the Fundamental Physics Constants: 2014, Mohr *et al.*[1]

Conversion Factors

Conversion Factors	
$1\,\text{Å}$	$= 0.1\,\text{nm}$
	$= 10^{-4}\,\mu\text{m}$
	$= 10^{-8}\,\text{cm}$
	$= 10^{-10}\,\text{m}$
$1\,\mu\text{m}$	$= 10 \times 10^{4}\,\text{Å}$
	$= 10^{3}\,\text{nm}$
	$= 10^{-4}\,\text{cm}$
	$= 10^{-6}\,\text{m}$
$1\,\text{eV}$	$= 1.60218 \times 10^{-19}\,\text{J}$

Powers of Ten

10^{24}	yotta	Y
10^{21}	zetta	Z
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	K
10^{2}	hecto	h
10^{1}	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a
10^{-21}	zepto	z
10^{-24}	yocto	y

Acronyms

AFM atomic force microscopy

SEM scanning electron microscope

Chapter 1

Introduction and Motivation

1.1 The Advent of Two-Dimensional Materials

1.2 Challenges in Two-Dimensional Materials

Chapter 2

Experimental Setup and Device Fabrication

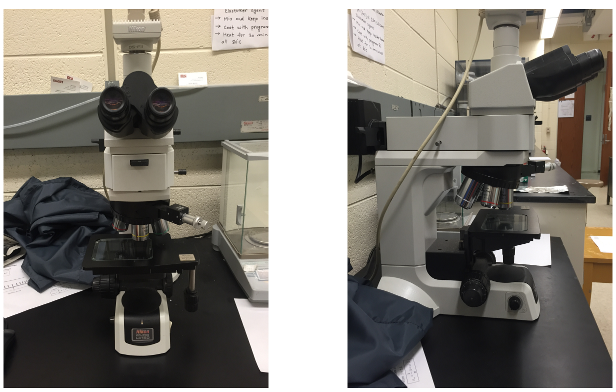
2.1 Sample Preparation

2.1.1 Synthesis of Crystal Material

2.2 Preparation of Atomically Thin Two-Dimensional Materials

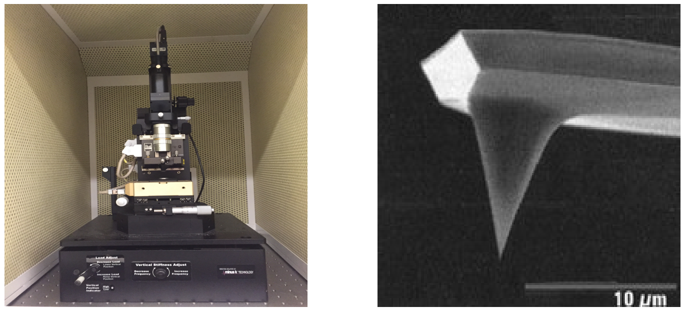
2.2.1 Exfoliation of Atomically Thin Materials

2.2.2 Characterization of Atomically Thin Materials



(a) (b)

Figure 2.1: (a) Optical microscope front view. (b) Optical microscope size view.



(a) (b)

Figure 2.2: (a) Front view of AFM setup. (b) AFM cantilever tip.

2.3 Stacking and Assembly of Two-Dimensional Materials

2.3.1 PDMS Film Preparation

2.3.2 PDMS Transfer Method

2.3.3 PC Film Preparation

2.3.4 Wet PC Transfer Method

2.3.5 Dry PC Transfer and Sequential Pickup Methods

2.4 General Fabrication Processes

2.4.1 Electron Beam Lithography

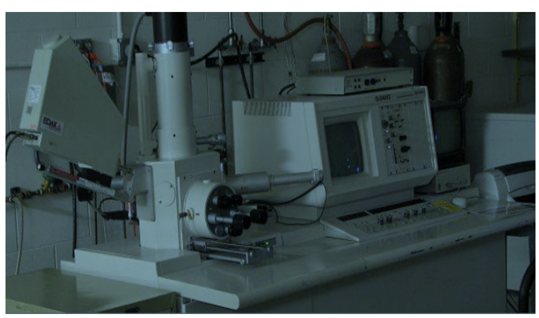


Figure 2.3: Control panel and electron beam writing system using a SEM.

2.4.2 Photolithography

2.4.3 Metal Deposition

2.4.4 Lift Off

2.4.5 Sample Annealing

Chapter 3

Chapter Title

3.1 Section Title

Chapter 4

Chapter Title

4.1 Section Title

References

[1] PJ Mohr, DB Newell, and BN Taylor. Codata recommended values of the fundamental constants 2014,(2015). *arXiv preprint arXiv:1507.07956*, 2015.

Autobiographical Statement

Name: Kraig Andrews

Education:
M.S. Physics, Wayne State University, Detroit, Michigan, 2017
B.S. Physics, Michigan State University, East Lansing, Michigan, 2014 B.S. Astrophysics, Michigan State University, East Lansing, Michigan, 2014
Professional Experience:
Some Job, Dept. of Physics and Astronomy, Somewhere, Year
Publications: "Paper Title" Journal Name

Your autobiographical statement.